

Clustering at high redshifts
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RXJ1716.6+6708: a protocluster at $z=0.81$?

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Abstract.

At $z=0.809$, RXJ 1716.6+6708 is the second most distant X-ray selected cluster so far published and the only one with a large number of spectroscopically determined cluster member velocities. The optical morphology of RXJ 1716.6+6708 resembles an inverted S-shape filament with the X-rays coming from the midpoint of the filament. The ROSAT HRI contours have an elongated shape that roughly coincide with the weak lensing contours. ASCA measures a low temperature, $kT=5.7$ keV. Keck-II LRIS spectra indicate a very high velocity dispersion, $\sigma_{los} = 1522$ km s⁻¹. While the temperature is commensurate with its X-ray luminosity, its velocity dispersion is much higher than expected from the $\sigma - T_X$ relationship of present-day clusters with comparable X-ray luminosity. RXJ 1716.6+6708 could be an example of a protocluster, where matter is flowing along filaments and the X-ray flux is maximum at the impact point of the colliding streams of matter.

1. Introduction

Clusters of galaxies at redshifts nearing one are of special importance since they may be caught at the epoch of formation. In hierarchical theories of structure formation, clusters of galaxies form from the high peaks in the original density field, thus they provide crucial constraints on the shape, amplitude, and temporal evolution of the primordial mass fluctuation spectrum. Despite their importance, the statistics for the abundance of high- z (~ 0.8 and beyond) clusters are poor since they are so difficult to locate. One of the cleanest ways to avoid sample contamination is the selection of high- z clusters by means of their X-ray emission. X-ray surveys are sensitive enough to detect distant clusters. Examples include MS1137+66, at $z=0.78$ and MS1054-03 at $z=0.83$ in the Medium Survey (Gioia et al. 1990; Gioia and Luppino, 1994; see also the detailed study on MS1054-03 by Donahue et al. 1996). Other X-ray surveys being conducted with ROSAT archive data are also finding distant clusters, for example the Wide Angle ROSAT Pointed Survey cluster at 0.83 (RXJ0152.7-1357, Ebeling et al. 1999) and the clusters discovered in the ROSAT Deep Cluster Survey (Rosati et al. 1998; Rosati et al. 1999). It is worth noticing that these high- z massive clusters are filamentary in optical with the X-rays following the elongation of the optical galaxies in most cases. Velocity dispersions and temperatures, when

available, show high values. Are we starting to observe the formation epoch of massive clusters?

2. The NEP Survey

Our group at the Institute for Astronomy in Hawai'i has been involved for several years in the optical identification of all the sources found in the North Ecliptic Pole (NEP) region of the ROSAT All-Sky Survey (RASS, Trümper et al. 1991; Voges et al. 1999). The NEP region is the deepest area of the RASS where the ROSAT satellite scan circles overlap and where the effective exposure time exceeds 35ks. The 9-year long identification program has been finally completed. A distant cluster, named RXJ 1716.6+6708, at $z=0.81$ was detected in the NEP with only 33 net photons (Henry et al. 1997; Gioia et al. 1999). This weak detection revealed a very interesting object. Keck-II spectroscopy and X-ray follow-up observations with the ROSAT High Resolution Imager (HRI) and with the ASCA satellite were performed and are presented here and, in more detail, in Gioia et al. (1999). Throughout this paper, we assume $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $q_0 = 0.5$.

3. Observations

Fig. 1 presents the optical image of RXJ 1716.6+6708. The cluster morphology is elongated in the NE-SW direction. Optical spectroscopy with the Low Resolution and Imaging Spectrograph (Oke et al. 1995) on the Keck-II telescope provided redshifts for 37 cluster members. An average redshift $z=0.8090\pm0.0051$ and velocity dispersion along the line of sight $\sigma_{los}=1522^{+215}_{-150} \text{ km s}^{-1}$ were obtained. From ASCA data a best-fit cluster rest frame temperature of $kT = 5.7^{+1.37}_{-0.58} \text{ keV}$ was measured for the cluster gas and a value $A = 0.43^{+0.25}_{-0.21}$ for the metallicity. The HRI reveals that RXJ 1716.6+6708 is morphologically complex at X-ray wavelengths too (see Fig. 2). The emission is clearly extended over a scale of roughly 1 arcmin ($\approx 500 h_{50}^{-1} \text{ kpc}$), and its shape is indicative of the non-regularity of this cluster. A total flux $f_{0.5-2\text{keV}} = (1.66\pm0.09)\times10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, and a luminosity $L_{0.5-2\text{keV}} = (4.57\pm0.24)\times10^{44} h_{50}^{-2} \text{ erg s}^{-1}$ are obtained. From the HRI surface brightness profile, assuming a constant temperature, $kT=5.7 \text{ keV}$, as measured by ASCA, the three-dimensional density distribution of the gas from the two-dimensional image was derived. Our estimates for the gas and gravitational mass within $\sim 1h_{50}^{-1} \text{ Mpc}$ using HRI data are $(8.9\pm2.1)\times10^{13} h_{50}^{-5/2} M_{\odot}$ and $(2.8\pm0.3)\times10^{14} h_{50}^{-1} M_{\odot}$. The total mass from X-rays is lower, even within the uncertainties, than the mass derived from weak lensing by Clowe et al. (1998), $M_{wl} = (5.2\pm1.8)\times10^{14} h_{50}^{-1} M_{\odot}$. We note however that the Clowe et al. (1998) mass determination includes the second clump of matter associated with the NE group of galaxies (see Fig. 2). This second clump is clearly separated in the Clowe et al. mass distribution map from the central cluster mass, and is not detected in the HRI.

4. Discussion

There are not many X-ray selected clusters at high redshift. The other published examples are the two clusters at $z \sim 0.8$ from the EMSS. Similarly to MS1054-03, RXJ 1716.6+6708 has a high velocity dispersion which can be interpreted as a signature of non-virialization. RXJ 1716.6+6708 has an extended X-ray emission of about $1'$, centered on the cD galaxy and with an elongation in the same direction as the optical galaxies. The temperature of RXJ 1716.6+6708 is commensurate with the predictions from its X-ray luminosity from the $L_X - T_X$ relation by David et al. (1993) and Arnaud and Evrard (1999). The measured velocity dispersion however is much higher than expected from its temperature. Using the derived value from the HRI of $\beta = 0.42$ and the measured ASCA temperature in the equation $\beta = \frac{\mu m_p \sigma_v^2}{k T_{gas}}$ a velocity dispersion of about 600 km s^{-1} is obtained, much lower than measured. Conversely, using the $\sigma - T_X$ relationship (Girardi et al. 1996) a temperature of $11.5_{-1.6}^{+3.0} \text{ keV}$ would be expected for $\sigma = 1522 \text{ km s}^{-1}$. In other words in an isothermal potential the mass distribution of the cluster does not correspond to the isotropic one-dimensional velocity dispersion. RXJ 1716.6+6708 may be an example of cluster which has not reached virial equilibrium, its dynamical state may be in large part dominated by infall or merging and consequently the velocity dispersion is not representative of the virial temperature of the cluster. If there is any fraction of infalling galaxies which are bound to the cluster but not yet virialized, they could inflate the velocity dispersion. These galaxies in the cluster would be moving on radial orbits. It might well be that galaxies are infalling towards the center of the cluster, and while some galaxies have already reached (or crossed) the core region, some others are still moving along radial orbits towards its center. This is somewhat supported by the gradient in velocity dispersion which is seen between eleven galaxies to the NE and nine galaxies to the SW (a small effect but significant at 2.7σ). Numerical simulations have shown that the universe is composed of a web of filaments and voids on the scale of hundreds of megaparsecs. The clusters of galaxies form at the intersections of these filaments and grow with time from quasi-spherical systems to the spherical objects that we observe today. The initial formation of protoclusters is often described as matter flowing along filaments (Bond et al. 1996) with the X-ray flux maximum at the impact point of two colliding streams of matter. In this scenario the hot gas and the galaxies would not be in hydrostatic equilibrium and the transient velocity dispersion could be higher than expected from a virialized system. We are probably witnessing this process in this very distant X-ray selected cluster, and RXJ 1716.6+6708 might be more properly called a protocluster.

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Figure 1. The image is a 1024×1024 subarray extracted from the center of a 4500s exposure in the I-band taken by Luppino and Metzger with the UH $8K \times 8K$ CCD mosaic-camera on the CFHT prime focus. Thirty-seven cluster members with Keck-II spectroscopy are marked. North is up and East to the left.

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Figure 2. Left panel shows the core of the cluster with contours of the HRI flux overlaid, while the right panel shows a Keck-II R-band image of the same area with the weak lensing contours from Clowe et al. (1998) overlaid. Either panel covers an area of 2.75×2.75 arcmin² ($1.3 \times 1.3 h_{50}^{-2}$ Mpc² at the redshift of the cluster).

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